Discovering the SM Higgs boson at the LHC

$$pp \to h \to W^+W^- \to l^+l^-\nu\bar{\nu}$$

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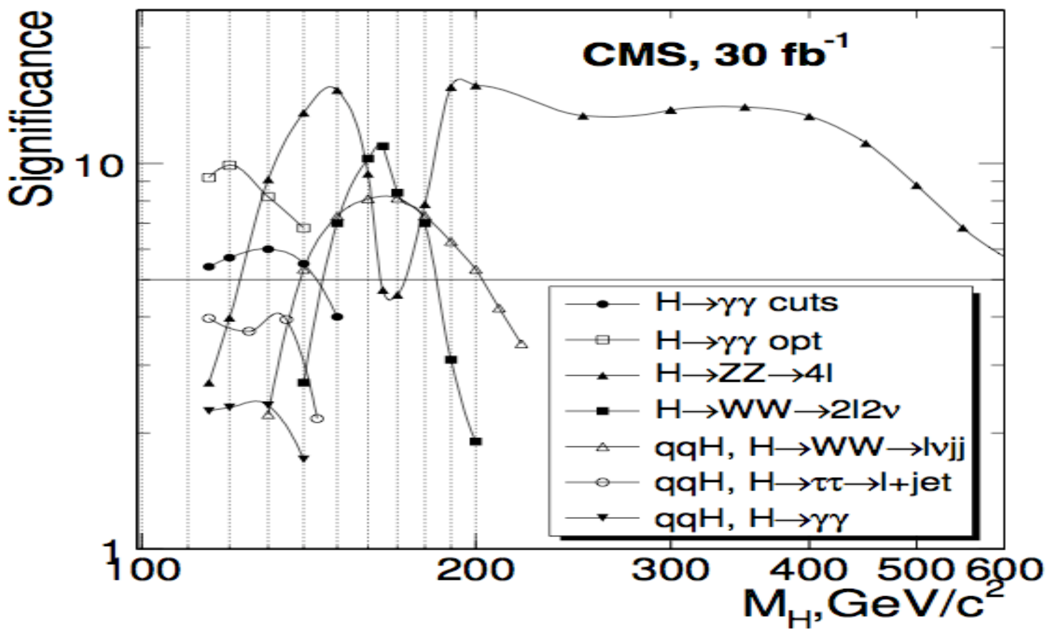
Outline

- Importance of the WW channel
- Difficulties in discovering the Higgs signal; clever selection of events
- Calculating the Higgs boson cross-section
  - from leading order to NNLO
  - from the total cross-section to fully differential ("experimental") cross-sections
- NNLO results for the signal cross-section
- Comparison of LO and NLO parton showers, with resummation and NNLO
- Sensitivity to jet algorithms, underlying event
- Conclusions

Higgs boson discovery

CMS/ATLAS have a full program to discover a SM Higgs boson with a mass 115-1000 GeV

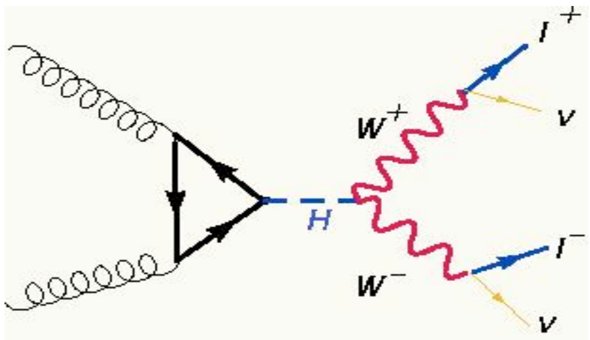


Notice a dip in the significance of all other channels when $M_h \approx 160$ GeV, on the WW pair threshold

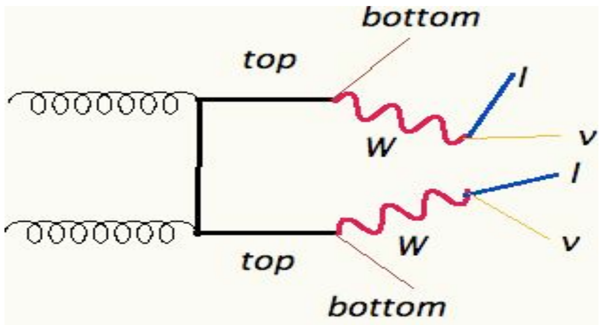
At threshold, we rely exclusively on the WW decay channels.

Signal and background

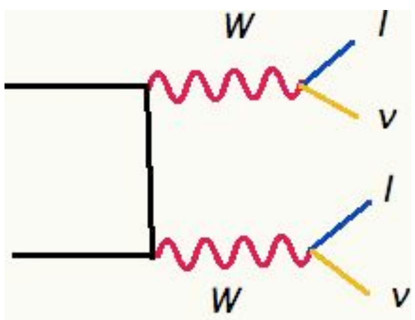
Gluon fusion signal

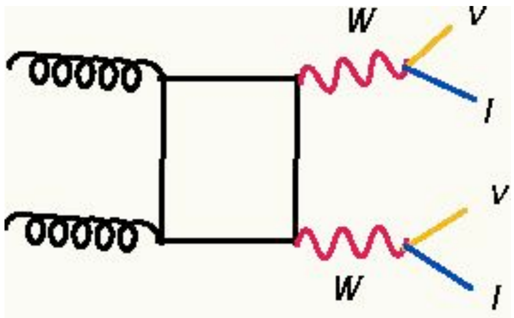


Top-pair background



WW irreducible background





Signal and background

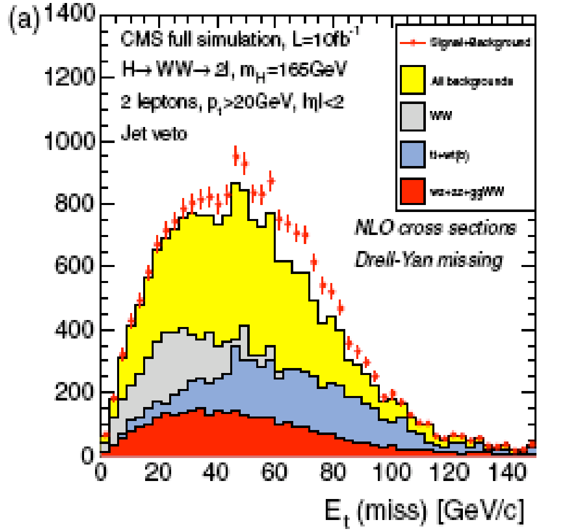
- Background processes are significantly larger than the Higgs signal. After basic cuts, requiring two high-pt (> 20 GeV) leptons at central rapidities (| eta | < 2),

$$\sigma(pp \to t\bar{t} \to ll\nu\nu + \text{jets}) \simeq 17pb^{-1}$$

$$\sigma(pp \to WW, ZZ \to ll\nu\nu) \simeq 1.4pb^{-1}$$

$$\sigma(pp \to H \to ll\nu\nu) \simeq 0.4pb^{-1}$$

A "counting" measurement, neutrinos escape, no narrow peak reconstruction



Davatz, Dittmar, Giolo-Nicollerat

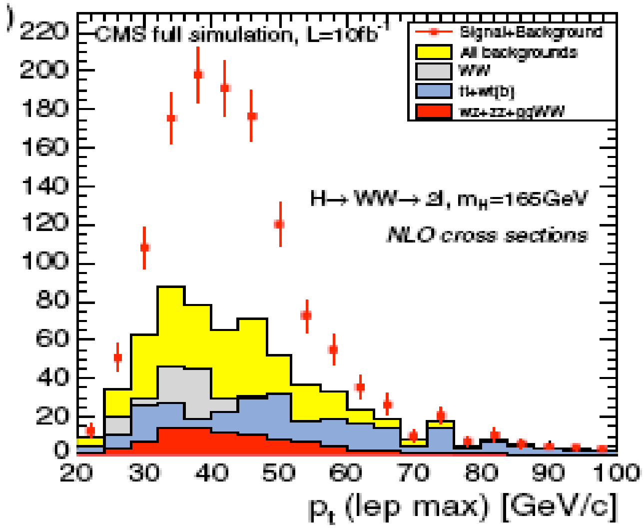
After clever cuts

A very good (1-2)/(1) Signal to Background ratio is achieved with clever cuts

(Dittmar, Dreiner 1997)

- leptons from the signal fly at small angles

- top background produces jets



Davatz, Dittmar, Giolo-Nicollerat

Signal selection cuts

(Davatz,Dittmar,Nicollerat)

Table 9. The expected number of events for an integrated luminosity of 1 fb^{-1} for a 165 GeV Higgs boson for the two-electron, two-muon and electron-muon final states. The relative efficiency with respect to the previous cut is given in parentheses. The W decay into τ are not taken into account. The last line shows the total selection efficiency together with the uncertainty from the limited Monte Carlo statistics.

$m_H = 165$ GeV	WW $\to$ ee	WW $\to \mu\mu$	WW $\to$ eμ
$\sigma \times \mathrm{BR}(e, \mu)$ [fb]	262	262	524
L1 + HLT	190 (73%)	217 (83%)	394 (75%)
2 lep, $\lvert\eta\rvert < 2$, $p_T > 20$ GeV	77 (41%)	106 (49%)	176 (45%)
$\sigma_{IP} > 3$, $\lvert\Delta z_{lep}\rvert < 0.2$ cm			
$E_T^{miss} > 50$ GeV	53 (68%)	79 (75%)	124 (71%)
$\phi_{\ell\ell} < 45$	30 (57%)	46 (58%)	71 (57%)
12 GeV $< m_{\ell\ell} <$ 40 GeV	22 (74%)	35 (76%)	53 (75%)
Jet veto	12 (52%)	19 (54%)	28 (53%)
30 GeV $< p_T^{\ell\max} <$ 55 GeV	10 (87%)	16 (85%)	24 (86%)
$p_T^{\ell\min} > 25$ GeV	9.0 (90%)	14 (85%)	21 (87%)
ε_{tot}	$(3.4 \pm 0.2)\%$	$(5.3 \pm 0.3)\%$	$(4.0 \pm 0.2)\%$

“Scary” cut efficiencies

The cuts reduce dramatically the background, with an efficiency of about 0.2% for top-pair and 1% for W-pair production. Only about 5% of the signal events pass the cuts!

-Do we understand H, ttbar, WW production accurately in such very small regions of phase-space?

- Theoretical work was/is needed on all three processes. The background simulations (extrapolations) will be verified against data away from the signal region.

- The signal can only be studied theoretically!

Higgs total cross-section

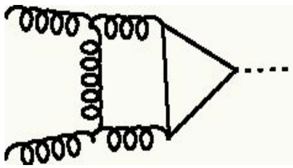
Very large perturbative corrections

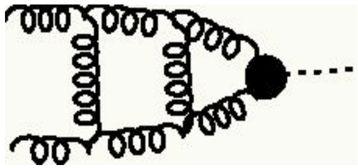
$$\frac{\sigma(NLO)}{\sigma(LO)} \approx 1.7$$

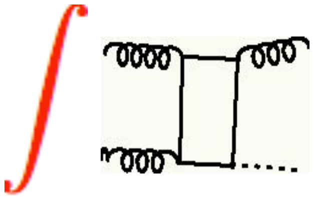
Dawson; Spira,Djouadi,Zerwas

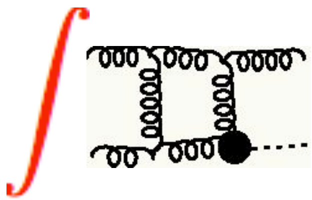
$$\frac{\sigma(NNLO)}{\sigma(LO)} \approx 2$$

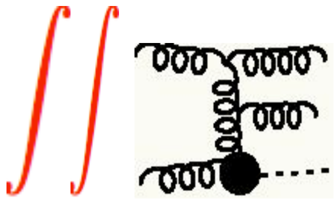
Harlander,Kilgore; CA,Melnikov; Ravindran,Smith,van Neerven











From total to differential cross-sections

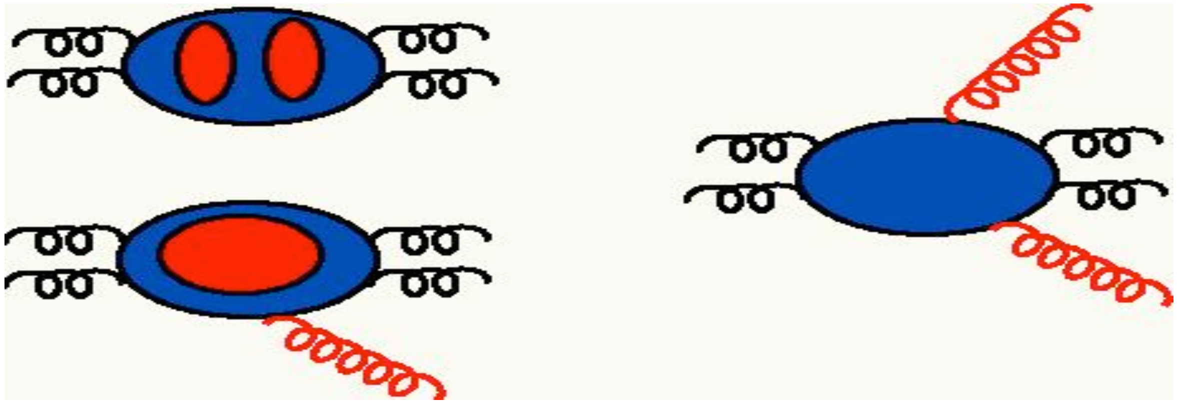
At NLO we compute any type of cross-section (differential or total) if the virtual amplitudes are known (Giele,Glover,Kosower; Frixione,Kunszt,Signer; Catani,Seymour; ...). Differential cross-sections at NNLO is a novel capability in perturbative computations. For colliders:

- Drell-Yan rapidity distribution, CA,Dixon,Melnikov,Petriello (03)
- $e^+e^- \to 2$jets CA,Melnikov,Petriello(04); Gehrmann,Gehrmann,Glover(04), Weinzierl(06)
- $pp \to H+X$ CA,Melnikov,Petriello(04)
- $pp \to H+X \to$ photons+X CA,Melnikov,Petriello (05) ; Catani,Grazzini (07)
- $pp \to W,Z+X$ Melnikov,Petriello (06)
- $pp \to H+X \to WW+X$ CA,Dissertori,Stöckli (07) ; Grazzini (08)
- $e^+e^- \to 3$jets Gehrmann,Gehrmann,Glover,Heinrich (07)

Subtraction at NNLO

(Gehrmann,Gehrmann,Glover,Heinrich; Catani,Grazzini; Weinzierl; Kosower; Grazzini,Frixione; Kilgore; del Duca,Trocsanyi,Somogyi; Daleo)

Proof of KNL theorem at every single phase-space point



- *Perform one and two-loop integrations (analytically)*
- *Subtract the (universal) infrared limits of real radiation amplitudes (locally) and integrate numerically*
- *Integrate (analytically) the subtracted terms*

Sector decomposition

(CA,Melnikov,Petriello; Binoth,Heinrich;
CA,Beerli,Daleo; Lazopoulos,Melnikov,Petriello)

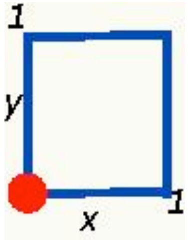
NLO and NNLO cross-sections with contributions from loop and real radiation amplitudes are nothing more than multi-dimensional integrals with singularities in d=4 dimensions (and threshold singularities...).

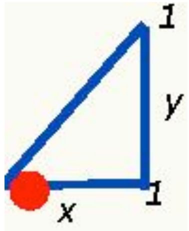
- Write multi-dimensional phase-space or Feynman parameter integrals
- Scan for singularities when d = 4
- Divide recursively the integration region until all overlapping singularities are fully factorized as poles of a single integration variable.
- For loop integrals, deform the multidimensional contours of integration (Nagy,Soper) to avoid threshold singularities.
- Subtract locally singularities in d =4 and Taylor expand

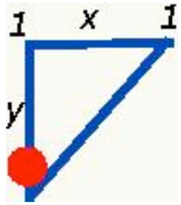
Sector decomposition example

(Hepp; Denner,Roth; Binoth,Heinrich)

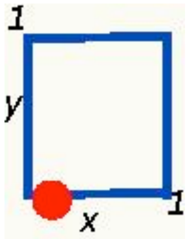
Factorize:

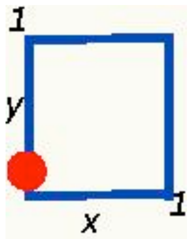






$$\int_0^1 dx dy \frac{x^\epsilon y^\epsilon}{(x+y)^2} = \int_0^1 dx \int_0^x dy \frac{x^\epsilon y^\epsilon}{(x+y)^2} + \int_0^1 dy \int_0^y dx \frac{x^\epsilon y^\epsilon}{(x+y)^2}$$





$$= \int_0^1 dx \int_0^1 dy \frac{x^{-1+2\epsilon} y^\epsilon}{(1+y)^2} + \int_0^1 dx \int_0^1 dy \frac{y^{-1+2\epsilon} x^\epsilon}{(x+1)^2}$$

Sector decomposition example

Subtract:

$$\int_0^1 dx\, f(x,\ldots) x^{-1+\epsilon} =$$

$$\int_0^1 dx\, f(x,\ldots) \left\{ \frac{1}{\epsilon}\delta(x) + \sum_{n=0}^{\infty} \frac{\epsilon^n}{n!} \left[\frac{\ln^n x}{x}\right]_+ \right\}$$

Comments:

- *All, real and virtual, contributions can be done numerically*
- *Solves the underlying mathematical problem*
- *Based on automated algorithms but not a fixed recipe; implementation wisdom/experience essential.*

NNLO computation: $pp \to h \to W^+W^- \to l^+l^-\nu\bar{\nu}$

(CA,Stöckli,Dissertori)

- Used the fully differential NNLO program FEHiP for pp$\to$h+X (CA,Melnikov,Petriello)
- Added decay matrix-elements; large phase-space rejection required rethinking of numerical integration.
- Independent/parallel integration for individual sectors; tremendous improvement, with better integration adaptation and easy exploitation of cluster computing
- Computation of all NNLO results of our paper using 450 CPU's on average for a week.

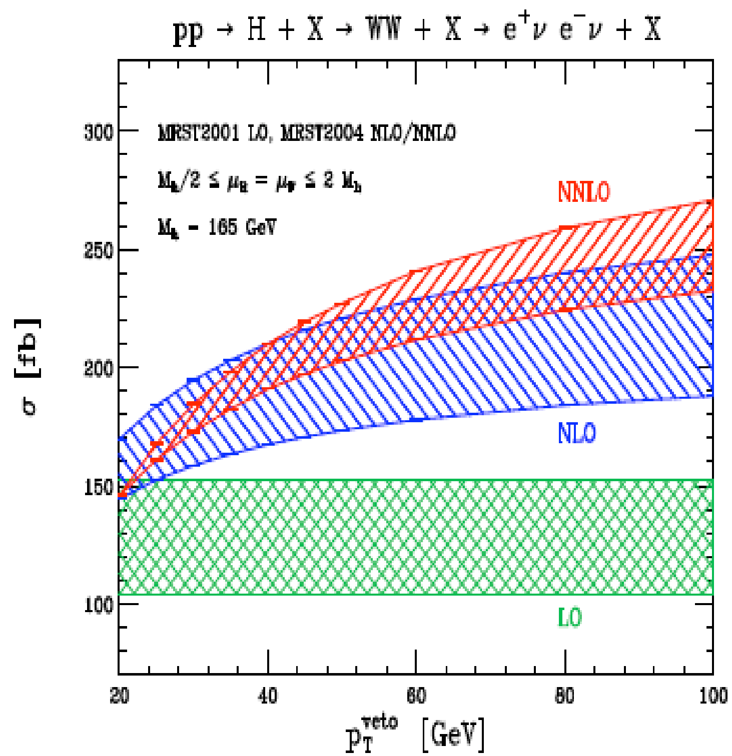
Jet Veto

-A jet veto does not change the LO cross-section.

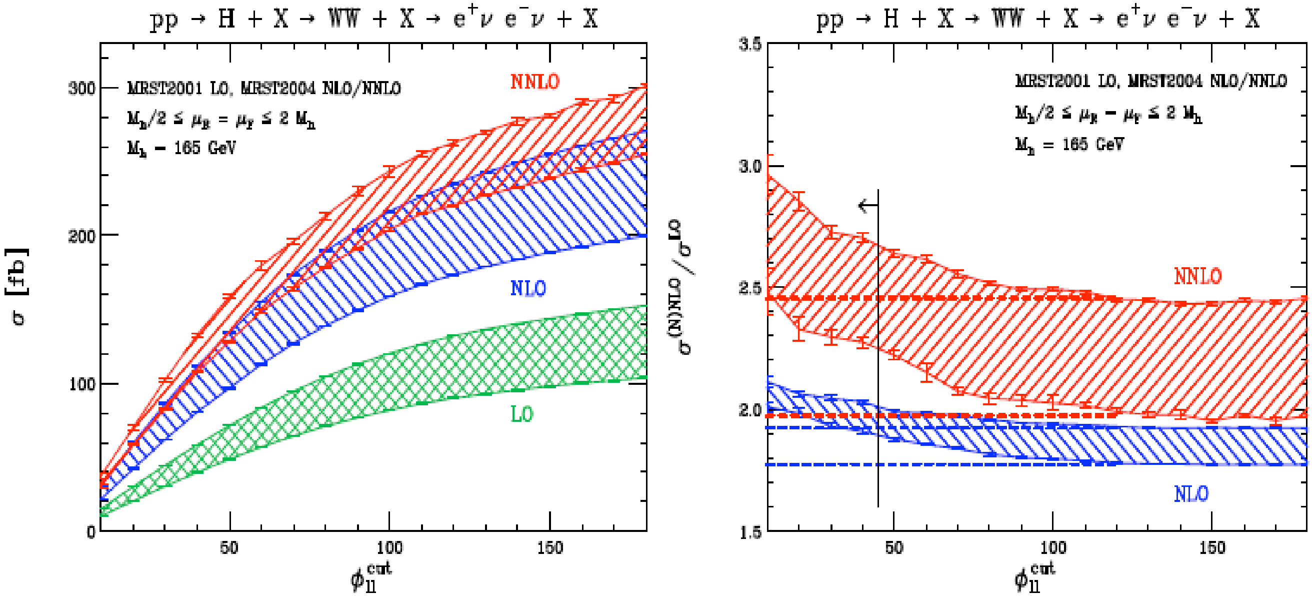
- It decreases NLO and NNLO corrections.

- Typical values: 25-40 GeV. Do we need resummation?

- Very small NNLO scale Variation. Realistic error?

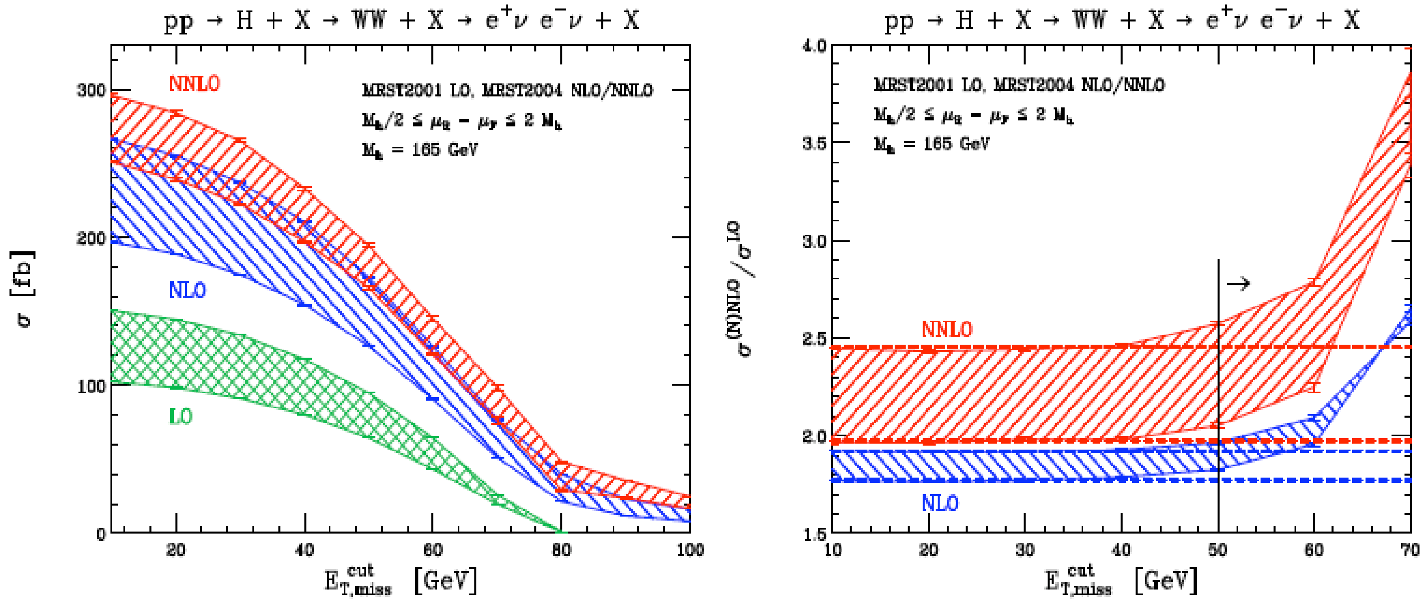


Transverse lepton angle



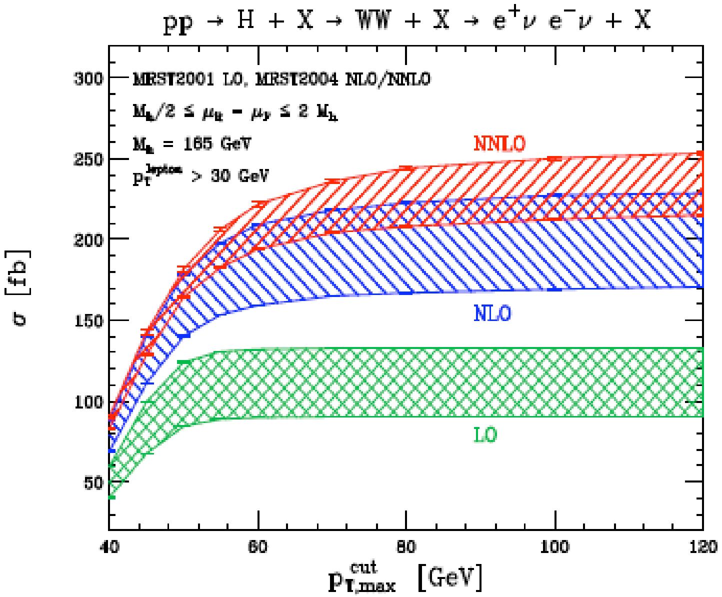
-Cut is placed where the NNLO and NLO corrections are not approximated by the K-factor for the total cross-section!

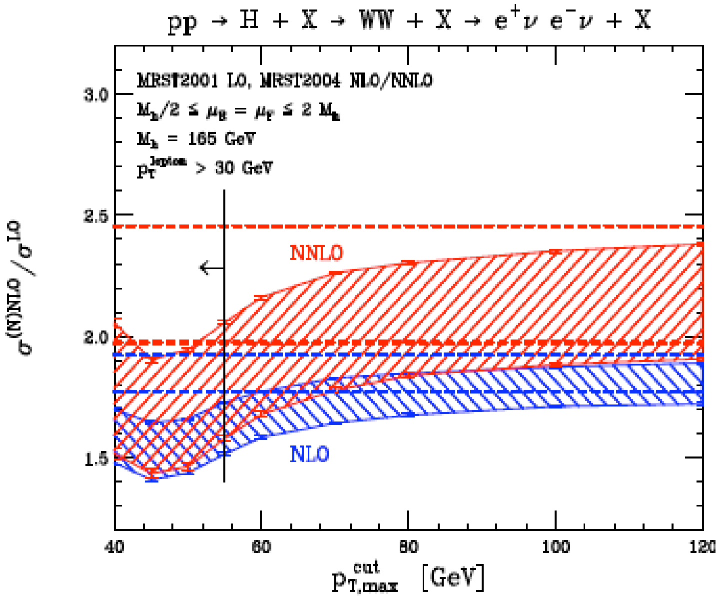
Missing transverse energy



The cut removes a significant part of the two-loop contribution. The LO phase-space is below 80 GeV. K-factor starts to deviate from inclusive K-factor.

Maximum lepton p_t





A reduction of NLO and NNLO corrections (similar trend in the jet-veto). K-factor significantly different than in inclusive cross-section.

Signal cross-section

After all cuts are applied:

$\sigma(\mathrm{fb})$	LO	NLO	NNLO
$\mu = \frac{M_{\mathrm{h}}}{2}$	21.002 ± 0.021	22.47 ± 0.11	18.45 ± 0.54
$\mu = M_{\mathrm{h}}$	17.413 ± 0.017	21.07 ± 0.11	18.75 ± 0.37
$\mu = 2M_{\mathrm{h}}$	14.529 ± 0.014	19.50 ± 0.10	19.01 ± 0.27

! K-factors are very different than the inclusive cross-section

! Very small NNLO scale variation

! Did the cuts result to a very precise NNLO prediction?

Scale variation

{NNLO signal cross-section}

{Total NNLO cross-section times efficiency at mu = Mh}

μ_{ren} \ μ_{fac}	0.25	0.5	1	2
0.25	21.90 16.82±0.94	21.88 18.40±1.00	21.95 16.06±0.94	22.04 15.45±0.98
0.5	20.22 18.84±0.60	20.35 18.45±0.54	20.52 17.52±0.93	20.67 18.10±0.63
1	18.30 18.68±0.90	18.55 18.33±0.40	18.75 18.75±0.37	18.94 19.87±0.42
2	16.44 17.89±0.27	16.74 18.27±0.29	16.98 18.97±0.29	17.20 19.01±0.27

Reduced scale variation after signal discovery cuts!

Are the NNLO results valid?

We could hurry to declare a "victory" of fixed order perturbation theory for the signal cross-section:

- smaller higher order corrections after cuts
- smaller scale variation at NNLO

Is this accidental? Are even higher than NNLO corrections important?

DANGER: Cuts restrict the phase-space significantly. Corrections from NLO to NNLO are kinematically variant. Predominantly low p_t contributions where resummation may be required!

Parton shower event generators

Leading order parton showers:

- They describe the total cross-section at LO; underestimate it by a factor of 2!
- Include leading log, leading color re-summation. Is this enough for efficiencies?
- Unclear errors from various factorization scales and scale dependence of the efficiency.

MC@NLO (Frixione, Webber):

- Increase of NNLO cross-section due to high pt! Can the parton-shower account for this?
- Strong kinematic dependence of NNLO/NLO K-factor

Validation

- We cannot argue convincingly that the efficiency from event generators comes out right or that the cuts do not introduce a large sensitivity from multiple soft/collinear radiation beyond NNLO, unless we compare!
- The physics approximations in fixed order and parton-showers are quite different; a disagreement means that at least one of these approaches does not describe the physics process correctly in the signal phase-space (defined by the Dittmar-Dreiner cuts).
- A good agreement will give confidence to our tools.

Earlier comparisons

- NNLO vs MC@NLO for $pp \to h \to \gamma\gamma$

  Dissertori, Holzner, Stoeckli

- NNLO vs MC@NLO for $pp \to W \to e\nu$

  Melnikov, Petriello; Frixione, Mangano

In both cases a very good agreement in the cut acceptances was generally found!
Typical cuts for these processes remove events "democratically" from both low and high pt regions.
Our case is more dangerous since the cuts reject high pt events

Resummed pt distribution

- A NNLL with NNLO matching pt-resummation is achieved. (Bozzi, Catani, de Florian, Grazzini)
- The pt-distribution of the Higgs boson is an inclusive cross-section and cannot be used directly when many cuts are required.
- But it is a solid theoretical prediction for an observable which captures the qualitative features of the signal cross-section.
- It combines to the highest possible accuracy fixed order and resummation effects.

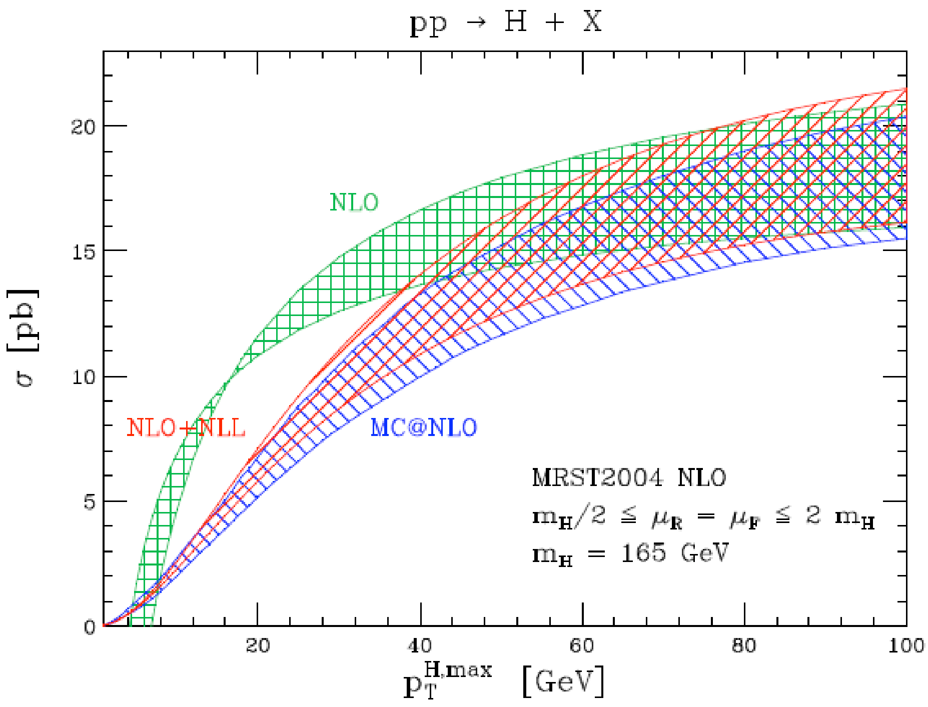
$$\sigma(p_T^{H,\max}) = \int_0^{p_T^{H,\max}} \frac{\partial\sigma}{\partial p_T^H}\, dp_T^H$$

How big integration range is needed?

- All results converge to the same value for an inclusive integration

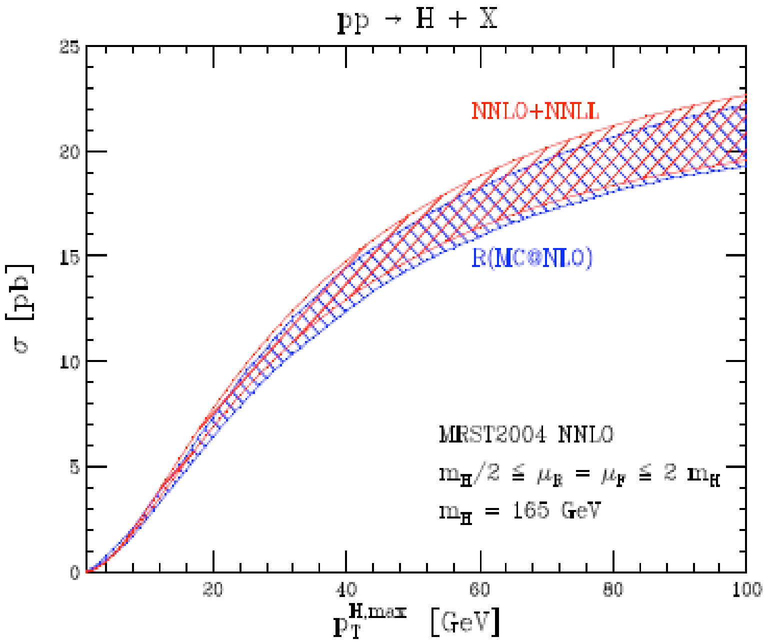
- Good agreement between MC@NLO and NLL

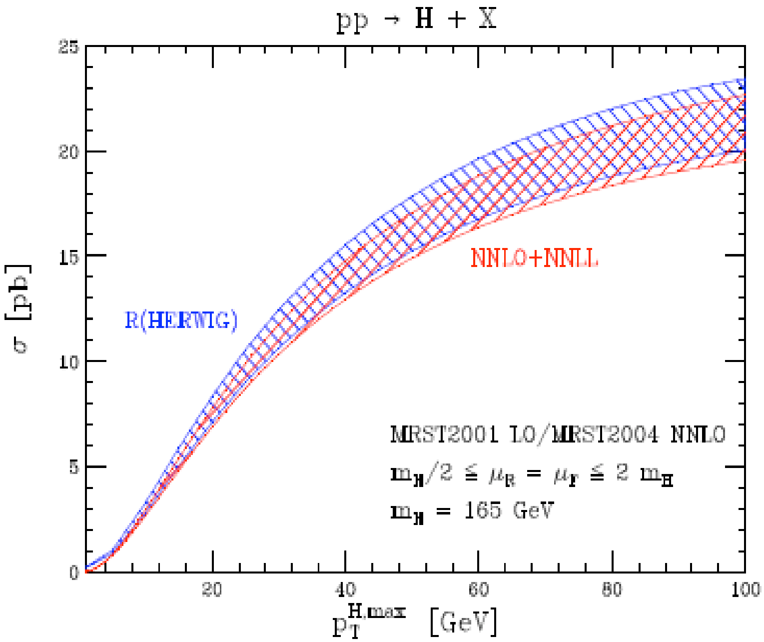
- NLO diverges for Higgs pt vetos above 35 GeV



HERWIG and MC@NLO vs NNLL

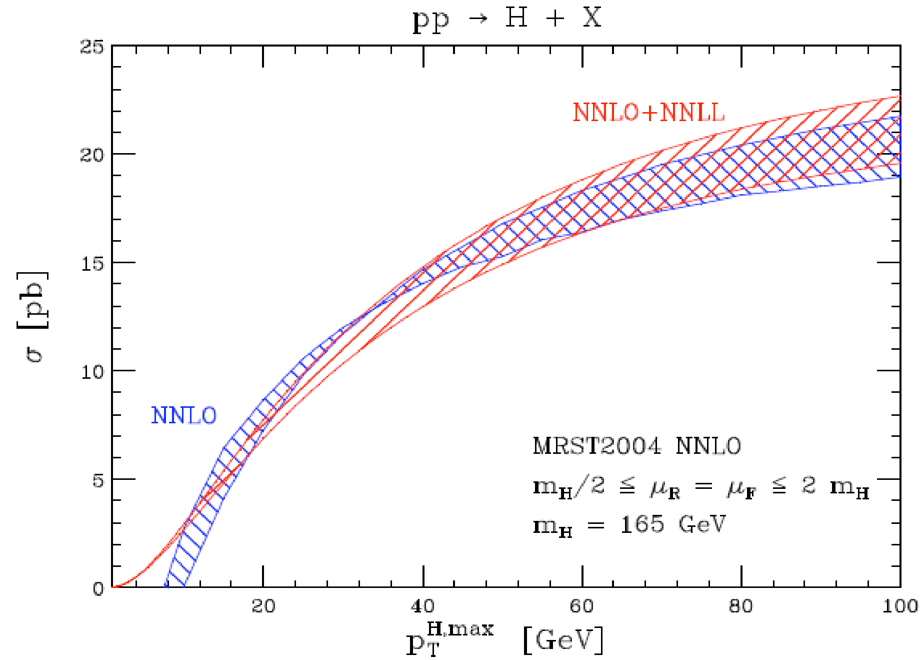
Normalized event generators to the NNLO total cross-section.
Both HERWIG and MC@NLO are in a very good agreement with NNLL resummation!





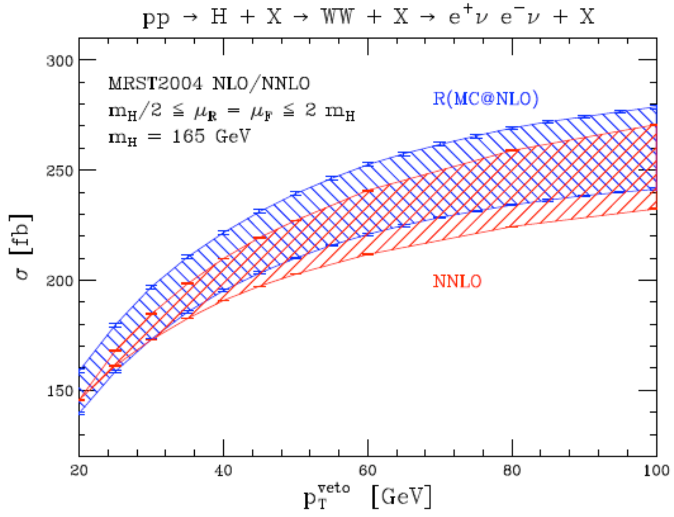
NNLO is spot on!

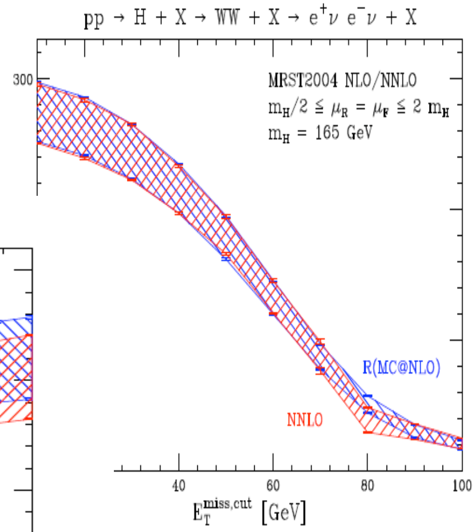
NNLO and NNLL agree spectacularly down to very small values of a Higgs pt veto!

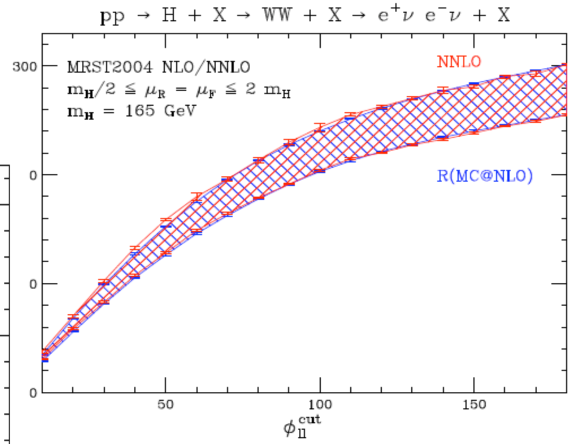


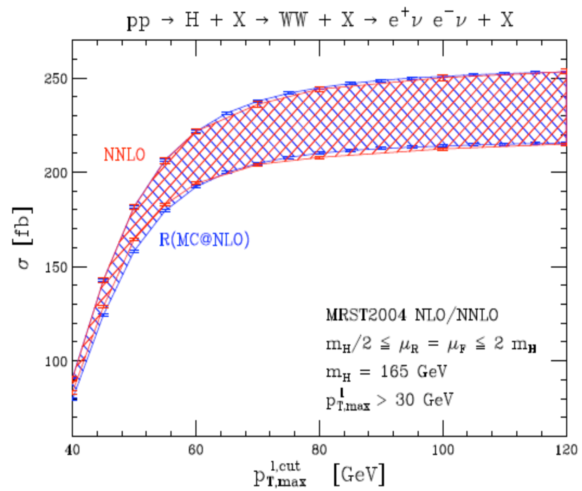
NNLO vs MC@NLO distributions

Again a spectacular agreement!







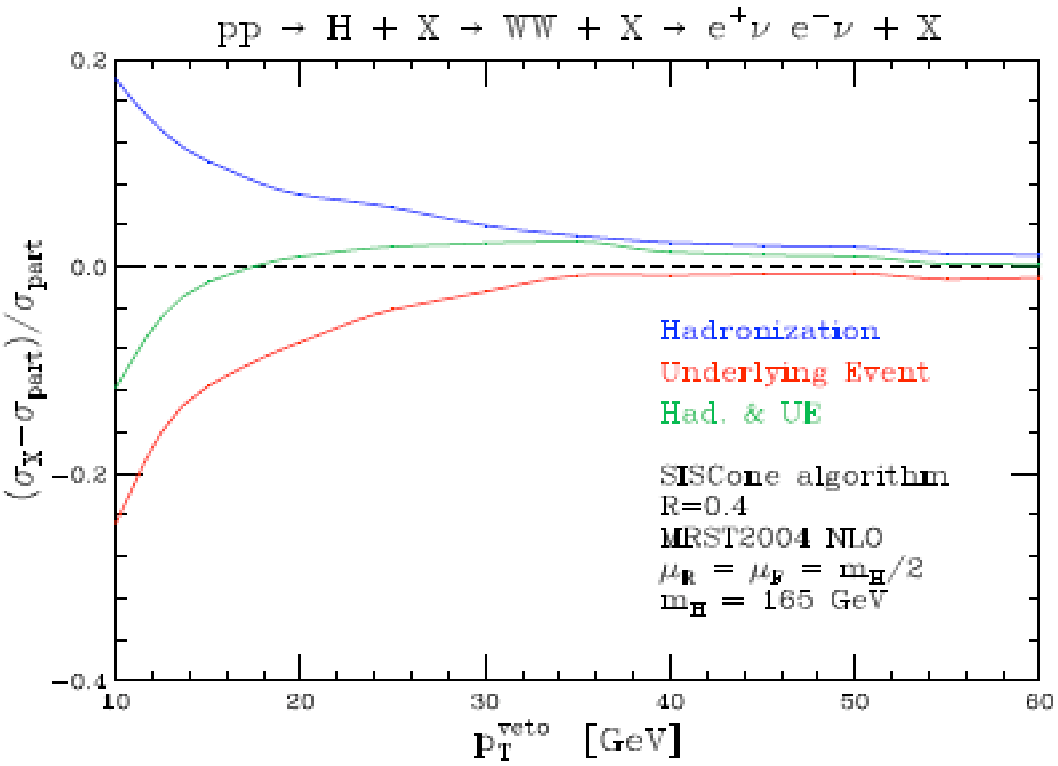


C. Anastasiou, ETH Zurich

Signal cross-section

σ_{acc} [fb] jet algorithm	$\mu = \frac{m_{\text{H}}}{2}$ SISCone	$\mu = \frac{m_{\text{H}}}{2}$ k_{T}	$\mu = 2\,m_{\text{H}}$ SISCone	$\mu = 2\,m_{\text{H}}$ k_{T}
LO	21.00 ± 0.02		14.53 ± 0.01	
HERWIG	11.16 ± 0.04	11.59 ± 0.04	7.60 ± 0.03	7.89 ± 0.03
NLO	22.40 ± 0.06		19.52 ± 0.05	
MC@NLO	17.42 ± 0.08	18.42 ± 0.08	13.60 ± 0.06	14.39 ± 0.06
R^{NLO}(HERWIG)	19.79 ± 0.07	20.56 ± 0.07	14.61 ± 0.05	15.17 ± 0.05
NNLO	18.84 ± 0.59	18.45 ± 0.54	18.76 ± 0.31	19.01 ± 0.27
R^{NNLO}(MC@NLO)	19.33 ± 0.09	20.43 ± 0.09	17.24 ± 0.07	18.24 ± 0.07
R^{NNLO}(HERWIG)	22.02 ± 0.08	22.88 ± 0.08	18.65 ± 0.07	19.38 ± 0.07

Hadronization & Underlying event



Jet vetos my lead to a sensitivity in hadronization and the UE.

Studied with HERWIG/JIMMY models in MC@NLO.

CANCEL each other largely...

Conclusions

-A (difficult) NNLO computation of the Higgs signal cross-section in the H-> 4 leptons channel is available

- A unique validation opportunity for MC@NLO, LO event generators, and NNLO for a process with known LARGE perturbative corrections and tricky cuts.

- Fixed order LO and NLO acceptances are significantly different than at NNLO.

- Very good agreement for the cut acceptances between MC@NLO and NNLO. Validated againsts NNLL resummation for the cumulative pt distribution.

- Robust theoretical predictions for the signal cross-section at the LHC (more work needed for Tevatron).

- The Higgs sector of the SM is not the only possible new physics! Work to improve further the S/B ratio in anticipation of smaller Higgs signal cross-sections (e.g. naturalness in RS models and "sweet spot" SUSY, ...)